MECHANICAL VIBRATION MEASUREMENT

SAMUEL LEE BRIDWELL

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S. L. Bridwell

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by

Samuel Lee Bridwell
Lieutenant, United States Navy

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PREFACE

In the calibration of mechanical vibration pickups, the accuracy of the calibration depends upon how accurately the displacement of the pickup can be measured.

This thesis has been a continuation of a study into the feasibility of calibrating vibration pickups by means of an optical interferometer system. The unit used in the study was designed by Professor E.K. Gatcombe in 1952. The unit was assembled by Lieutenant E.P. Appert in 1953, and he at that time, made a preliminary study of its utility. Work was done by this author from January 1954 through April 1954 at the United States Naval Postgraduate School, Monterey, California.

The author is indebted to Professor Gatcombe for his valuable guidance throughout the entire work and to Professor S.H. Kalmbach for his helpful assistance.

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TABLE OF SYMBOLS AND ABBREVIATIONS

a_f	acceleration in "G"'s, calculated from phototube output
a_p	acceleration in "G"'s, calculated from accelerometer output
A°	Angstrom units. 1 A° = 10^{-8} centimeters
A	Maximum displacement from neutral position
B	ratio of actual frequency to natural frequency
f	frequency in cycles per second
G	acceleration in earth's gravitational units
h	coefficient of viscous damping
m	peak-to-peak amplitude in oscilloscope grid units
n	number of pips per cycle
t	time in seconds
u	acceleration correction factor
w	frequency in radians per second
Y	instantaneous displacement from neutral position
Y_{acc}	acceleration in Y direction

CHAPTER I

SUMMARY

1. Introduction

The usefulness of an instrument capable of yielding an indication of the displacement, velocity, or acceleration of a body subjected to mechanical vibrations, is limited by the accuracy and reliability of the criteria set up to evaluate the response characteristics of the instrument.

If we may assume that an instrument has been designed which will faithfully reproduce its output signal when subjected to the same input disturbance, we are still confronted with the problem of interpretation of the output signal. For the seismic type instrument, the output is a function of the acceleration and the effective frequency of the disturbance.

In the calibration of a seismic pickup, the accuracy of the calibration will be directly dependent upon how accurately one knows and can describe the motion imparted to the pickup.

2. Objective of this thesis

This thesis is an investigation into the use of an optical secondary standard of displacement for a seismic pickup, specifically as applied to the development of an accelerometer pickup.

3. General methods employed

Figure 1 shows the schematic arrangement of the components employed in the test setup. These components include a mercury lamp, filters, a collimnating lens, silvered optical flats, a condensing lens, a field stop, a periscope, a photoelectric tube, and a means of visual presentation of the output of the phototube.

When the optical flats are made parallel (by external adjustments) the image of the extended source reflected in the air film between the two plane silvered flats produces the well known Haidinger fringes. A displacement of one optical flat by an amount equal to one-half of a wave length of the monochromatic light source will cause the central image of the fringe pattern to undergo one cyclic change, as from dark to light to dark. By proper adjustment of the optical stop and the phototube, the change in the central dot will be recorded on the cathode ray oscilloscope.

In the test setup, one of the silvered flats was caused to move by external means, and its motion recorded on the cathode ray oscilloscope. Also presented simultaneously on the same cathode ray oscilloscope was the output from a commercial seismic type accelerometer pickup; the accelerometer pickup having the same motion as the moving optical flat.

4. Findings

The interferometer principle provides an excellent means of measuring small displacements, provided that the total displacement is several wave lengths of the monochromatic light source. With the displacements accurately known, the calibration curve and the amplitude response curve of the pickup may be readily obtained. In principle the unit is capable of operation over a wide frequency and large amplitude range; however, in practise, there are limitations to both.

CHAPTER II

DESIGN CONSIDERATIONS AND CHANGES REQUIRED

1. The mercury light source

The original design provided for the light source to be contained within the structure of the calibration unit. Being so contained, the size of the light source was limited to about 40 watts. The power supply for this light was 2200 volts AC. The use of this 40 watt light source necessitated amplification in either the phototube or between the phototube and the cathode ray tube. If a stronger light source could be used, fewer stages of amplification would be required, and an improvement in the signal-to-noise ratio would be expected. The fact that the voltage supply was AC resulted in a rectified sine wave (power wave) being presented on the cathode ray tube under static conditions. When the optical flat was in motion, intelligence was lost at the low intensity portion of the power wave. If a stable DC light source could be incorporated in the unit, the presentation from the interferometer could be more readily utilized.

2. The photoelectric tube

An RCA 1-P-21 photomultiplier tube was used in an attempt to gain the necessary amplification and at the same time keep the signal-to-noise ratio high at the recording instrument. Only at the very highest rate of fringe changes did the signal-to-noise ratio introduce difficulty in interpretation of the presentation. A newly designed DuMont phototube was ordered, but had not been delivered at the time the evaluation was stopped. A filter was inserted between the photomultiplier and the cathode ray tube,

and it was quite effective in reducing the noise, but it also attenuated the signal at the higher rates of fringe change. As discussed above, a more intense light source would possibly improve the presentation. Reference to Figure 2 illustrates one of the limitations to this system. You will note that the amplitude of the intelligence from the fringe changes decreases as the rate of change of fringes increases. Here again, a more intense light source may overcome this limitation. If it were possible to use a single stage phototube, the frequency response could be improved, since a photomultiplier introduces a frequency limitation.

3. The test stand

Initially the calibration unit was mounted on a Westinghouse Vibration Fatigue Motor (see Figure 3). The vibration motor field and the frame of the calibration unit were bolted rigidly together; both in turn being blocked so as to be fixed to ground. The moving optical flat and the acceleration pickup were vibrated sinusoidally by the armature of the vibration motor. This test stand proved to be of little value, since the entire mass vibrated with respect to ground. Several attempts were made to increase the rigidity of the test stand, but all were unsatisfactory. If the mass of the test stand with the frame of the calibration unit could be sufficiently increased, it is possible that flexible supports could be used. It is absolutely essential that the reference framework be stationary, since the prime importance of this calibration unit is to measure extremely small displacements and correlate them with the output of the accelerometer pickup being calibrated.

The calibration unit was next mounted in the largest "rigid body" available, see Figure 4. Even in this mounting, the unit was not immune

to extraneous disturbances, but their magnitude was reduced to the point where they could be neglected.

4. Stray noise pickup

Since very low voltages are used in the transmission of the intelligence from the phototube and the accelerometer, a minimum of shielding is necessary even for preliminary study, and for actual calibration runs, a maximum of shielding would be required.

5. The guide springs

In this calibration unit, the moving parts are supported on, and guided by circular springs. The outer edge of the spring is secured to the stationary framework, and the moving masses attached at the center of these flat circular springs. The exciting force is applied to the moving masses and the springs transmit part of this exciting force to the framework. This transmitted force caused the motion of the supporting framework, as mentioned above. In an effort to reduce the degree of coupling between the moving members and the stationary members, the guide springs were reduced in thickness from 1/8th inch to 1/10th inch. This reduction produced an improvement, but the improvement was not as great as desired. Further reduction of the thickness of these springs was not attempted. It is believed that a much greater improvement could be gained by increasing the outside diameter of these guide springs.

CHAPTER III

INTERPRETATION OF THE RESULTS

1. The phototube output

Figure 5 is a series of exposures made of the phototube output presentation on the screen of the cathode ray tube. Also included in the picture is a signal representative of the amplitude and shape of the exciting force applied to the moving optical flat.

Each time the distance between the silvered optical flats was altered by one-half wave length of the mercury light source, the intensity of the central portion of the Haidinger fringe pattern passed through a complete cycle. For the mercury line 5461 A°, this corresponds to 10.75×10^{-6} inches in the separation of the plates.

Let us assume that the motion of the one optical flat may be described by the equation $Y = A \sin(wt)$, where Y is the instantaneous displacement, A is the maximum displacement from the neutral position, and w is the excitation frequency. If the intensity of the central portion of the fringe pattern is either maximum or minimum when the optical flat is in the neutral position, we may expect the following presentation:

$00.00 < A \nleq 5.38 \times 10^{-6}$ inches . . . 2 "pips" per cycle

$5.38 < A \nleq 10.75 \times 10^{-6}$ inches . . . 4 "pips" per cycle

$10.75 < A \nleq 16.13 \times 10^{-6}$ inches . . . 6 "pips" per cycle

etc.

If the amplitude A is an integral multiple of one-quarter of the wave length of the source light, the pips will be of even height. However, if the amplitude A is not an integral multiple of one-quarter of the wave length of the source light, or if the neutral position is not of maximum

or minimum intensity, the pips will not necessarily be of the same height. This fact is mentioned since it has a direct bearing on the interpretation of the presentation on the cathode ray tube. Referring again to Figure 5, note the change in the presentation as the amplitude of the exciting force is increased. The first (upper) presentation indicates an amplitude equal to or less than 5.38×10^{-6} inches; the last presentation (lower) indicates an amplitude between 10.75×10^{-6} inches and 13.44×10^{-6} inches. The possible error in this last estimate may be as great as 30%; if however, it were possible to have an amplitude of, say, ten fringe changes (107.5×10^{-6} inches) the possible error would be reduced to 2.5%.

If the frequency of the exciting force is known, with the above estimate of amplitude, the acceleration may be computed with the aid of equation $Y_{acc} = -Aw^2 \sin(wt)$. This equation will yield a fair description of the acceleration (depending upon the accuracy of the amplitude and frequency) if the exciting force may be assumed to be sinusoidal. Other equations may be derived if the shape of the exciting force is known or can be accurately estimated. If the exciting force cannot be accurately described, for the case of transients in particular, then a timing trace must be utilized with the presentation from the phototube and a point by point acceleration determined.

Figure 2 is representative of the presentation from the phototube and the commercial accelerometer. The photograph was made with a high speed oscillo-record camera manufactured by Fairchild-Smith Company. The motion of the film supplies the time axis, while the outputs from the phototube and the accelerometer supply the Y-axis signals. The film in this case

was transported at the maximum speed of the camera, nominally sixty inches per second. Since the rectified sine wave has a repetitive frequency of twice that of the power supply, the exact film transport speed was of little importance.

The exciting force in this case was a transient induced by lightly tapping the framework carrying the accelerometer and the moving optical flat. The transient response at the instant of the application of the external force was too rapid to be registered on the film. Pictured here is the die away, with the system oscillating at its natural frequency. Very little intelligence can be gleaned from this photograph; direct viewing of the film from which this print was made is somewhat better, but at the point where the number of pips per cycle becomes barely discernible above the noise, the number of the pips is so small that possible error rules out any reliable use for calibration purposes.

The output of the accelerometer is a voltage proportional to the acceleration of the case of the accelerometer. Normally this output voltage is reduced to an acceleration by means of a factory supplied multiplying constant and the supply voltage. If the accelerometer is used above its designed range, it must further be modified by a factor which is a function of its damping coefficient and the frequency of oscillation.

Figure 6 is another picture of a presentation similar to that in Figure 2, being more legible in some respects.

CHAPTER IV

CONCLUSIONS

1. Feasibility of the Method

The author is of the opinion that the described method of measurements of small displacements can possibly be successfully applied as a means of calibrating acceleration pickups. The method deserves further investigation. The unit used in this investigation has probably served its purpose, and rather than attempt to modify this unit, a new unit should be designed duplicating its desirable features and attempting to overcome its shortcomings. Specific suggested improvements are: (1) a more intense light source of constant intensity, (2) a lesser degree of coupling between the two optical flats, (3) improvement in the transient response time of the phototube circuit, (4) a means of rigidly mounting the framework of the unit, and (5) a more reliable means of recording the output of the unit, especially where rapid changes in the output are encountered.

2. Suggestions for further study

Worthy of investigation is the possibility of using the output of the phototube as the input to an automatic computer and plotter, where the output could then be a presentation of the variable actually sought, in this case, acceleration. Where the output of the phototube is too rapid for accurate recording in the usual manner, the possibility of using magnetic tape and/or wire recording as an intermediatory step should not be overlooked.

APPENDIX I

TEST RUN DATA

1. Equipment

The following equipment was used in the test setup: Westinghouse Vibration Fatigue Motor, Type GS; calibration unit; commercial accelerometer pickup; 40 db amplifier; dual beam oscillograph, with recording camera.

2. The test setup

The calibration unit was mounted on the vibration motor, Figure 3, with the accelerometer pickup in place on the top of the calibration unit. The excitation from the vibration motor was assumed to be sinusoidal. The accelerometer pickup was supplied by a 5.9 volt wet cell battery, the output of the pickup was fed through the 40 db amplifier, and then into one of the channels on the oscilloscope. The output of the phototube was fed directly into the oscilloscope. The oscilloscope was adjusted for optimum definition and the presentation recorded with the recording camera. A 50 millivolt calibration voltage was recorded with the 360 cycle per second display.

3. Reducing the data

The peak-to-peak amplitude of the accelerometer pickup output was then measured and converted to millivolts by comparison with the calibrating voltage, reduced by one-half to obtain peak amplitude, then reduced by 40 db (1/100th) to obtain millivolts output from the pickup itself. This voltage, by use of the factory supplied constant and the factory supplied equation, was reduced to apparent acceleration. Since the excitation frequencies were outside the normal range for this pickup, it was necessary

to correct this apparent acceleration by the factor $1/u = \sqrt{(1-B^2)^2 + (2hB)^2}$ to obtain the indicated acceleration. For this particular accelerometer pickup, $B = f/95$, where f is the exciting frequency in cycles per second, and h was assumed from factory literature to be 0.65. The final equation for reducing the peak-to-peak amplitude becomes:

$$a_p = \frac{m \times 50}{u \times 19 \times 100 \times 2 \times 1.597 \times 5.9} = \frac{m}{u} \times 1.4 \times 10^{-3}$$

where a_p is in Gs of acceleration and m is in oscilloscope grid units.

The phototube output is converted to an acceleration by counting the number of "pips" per cycle, dividing this by 4, multiplying by $10.75 \times 10^{-6} \times w^2$ and dividing by 386 (in/sec^2), where $w = 2\pi f$. This yields a_f in Gs of acceleration. $a_f = n \times f^2 \times 2.745 \times 10^{-7}$ where n is the number of "pips" per cycle.

4. Results

Tabulated below is the result of the computations based on the data presented in Figures 7 and 8.

f	n	m	a_f	a_p	$\frac{a_p - a_f}{a_f}$
95	8	7	.020	.013	-.36
190	7	11	.070	.061	-.11
240	8	12	.127	.106	-.16
285	9	15	.201	.187	-.07
300	7	12	.173	.166	-.05
360	12	20	.427	.397	-.07
380	16	26	.635	.577	-.09
420	14	25	.678	.678	.00
475	16	28	.992	.975	-.02
480	18	32	1.138	1.138	.00

f	n	m	a_f	a_p	$\frac{a_p - a_f}{a_f}$
540	19	34	1.522	1.530	.01
570	15	31	1.362	1.556	.13
600	17	33	1.680	1.830	.09
660	12	33	1.435	2.215	.54
665	8	22	.972	1.502	.55
720	22	18	3.135	1.440	-.54
760	15	17	2.380	1.518	-.36
780	20	21	3.340	1.980	-.41
840	18	24	3.490	2.610	-.26
855	11	15	2.210	1.697	-.23
900	18	27	4.450	3.380	-.24
960	11	17	2.785	2.420	-.13
1020	7	8	2.000	1.290	-.36
1080	6	10	1.925	1.803	-.06

5. Conclusions

The data given above is typical of several runs made on the vibration motor. You will note that the error changes from 0.55 to -0.54 in a matter of 55 cycles per second change. This is explained by a consideration of the phase relationship between the motion of the driven members and the undesirable motion of the framework of the calibration unit and the vibration motor. It appears that at 665 cycles per second they were more in phase than they were at 720 cycles per second. Reducing the gain on the driving force altered the absolute magnitudes of the two outputs, but had little or no effect on their relative magnitudes.

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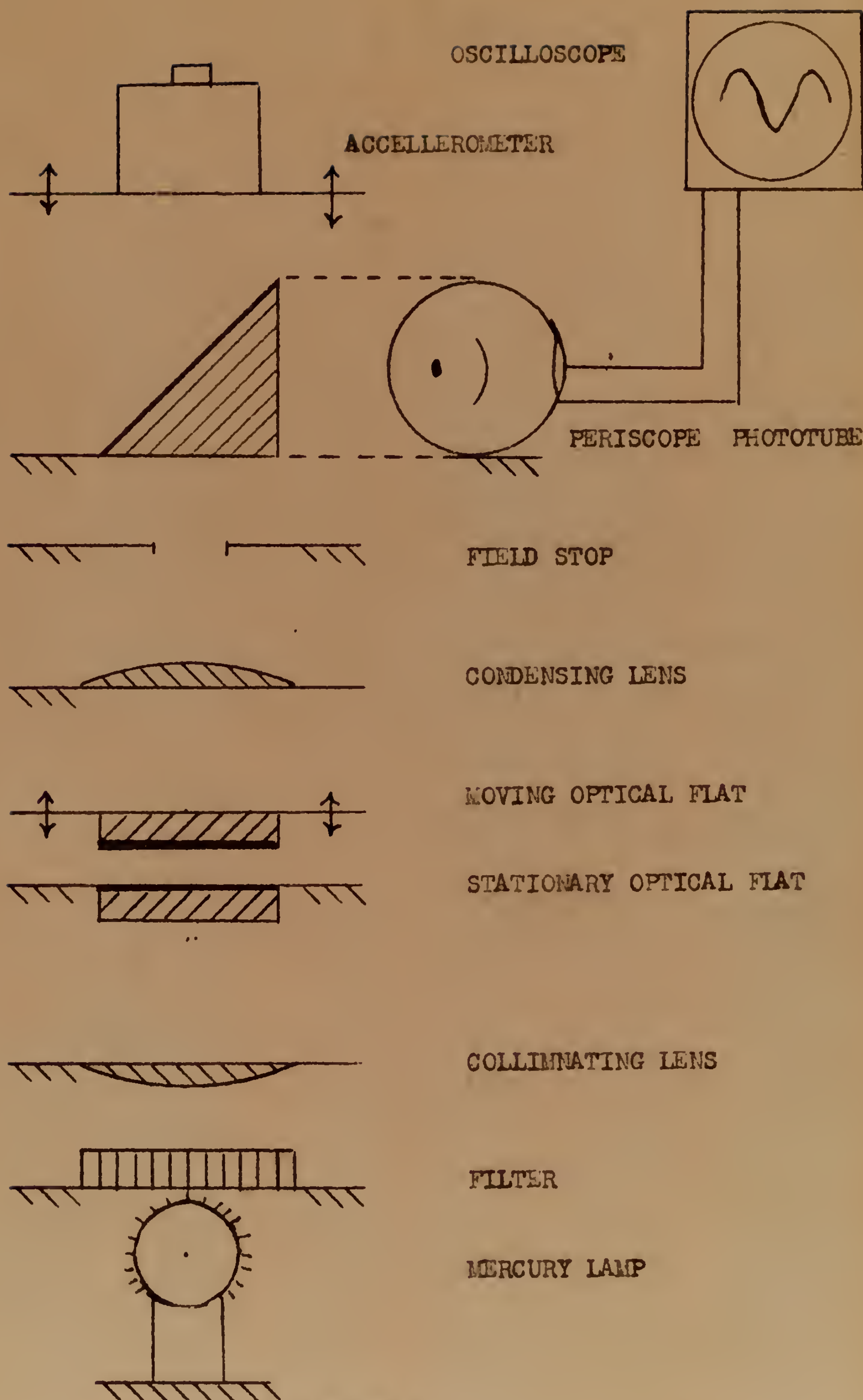
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PERISCOPE
PHOTOTUBE
FIELD STOP
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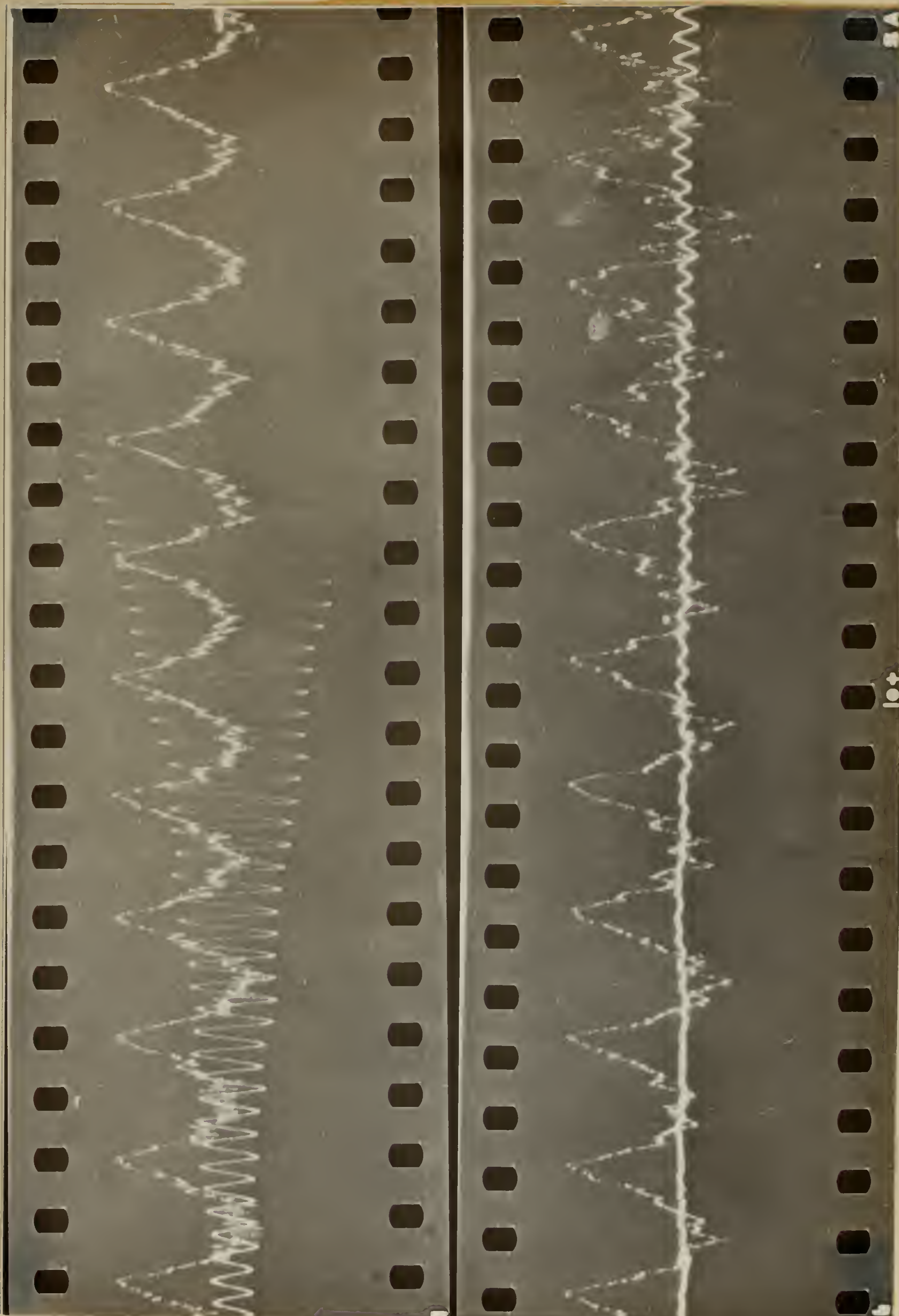
MOVING OPTICAL FLAT
STATIONARY OPTICAL FLAT
COLLIMATING LENS
FILTER
MERCURY LAMP

Figure 1



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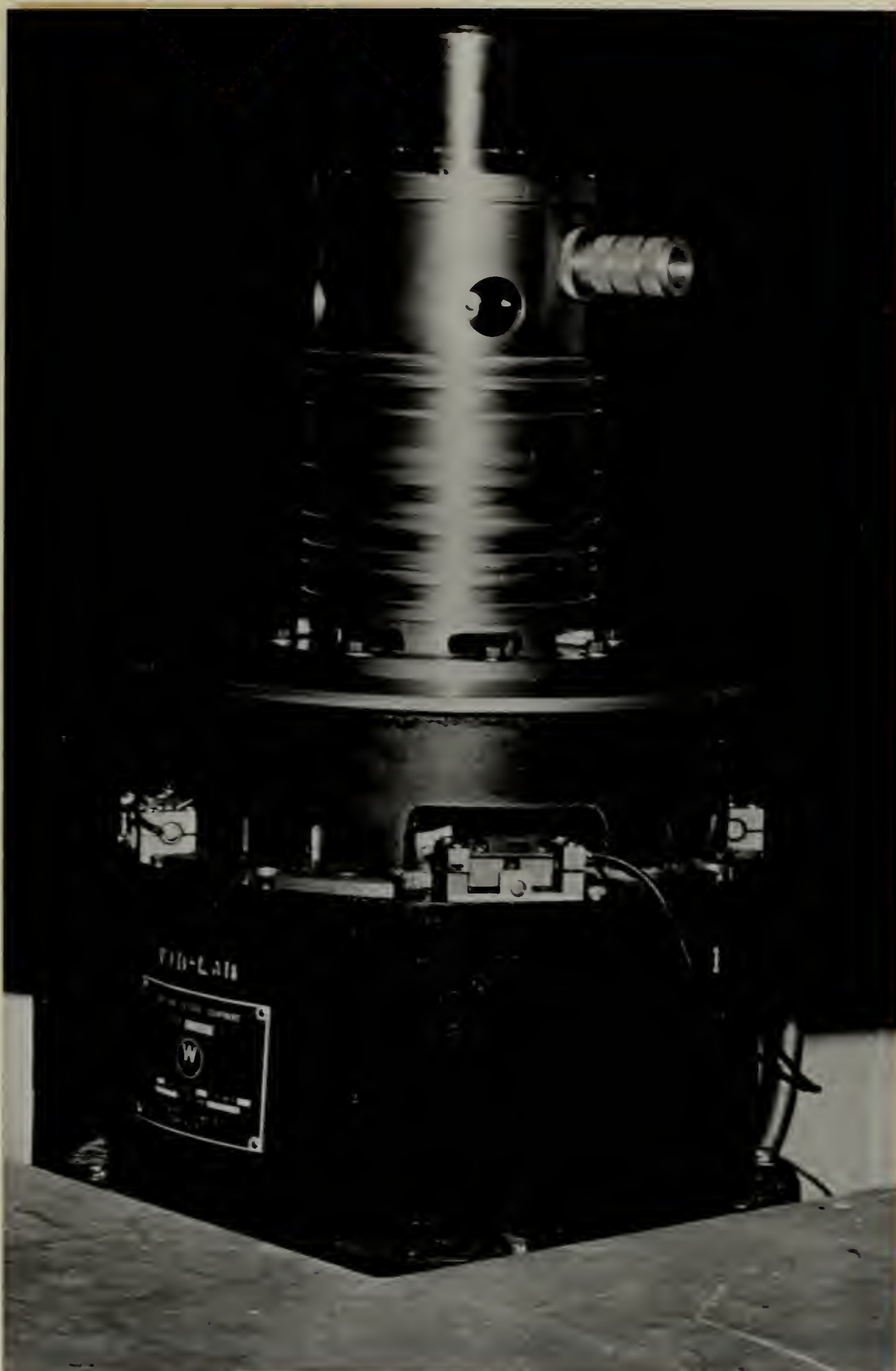

Figure 3

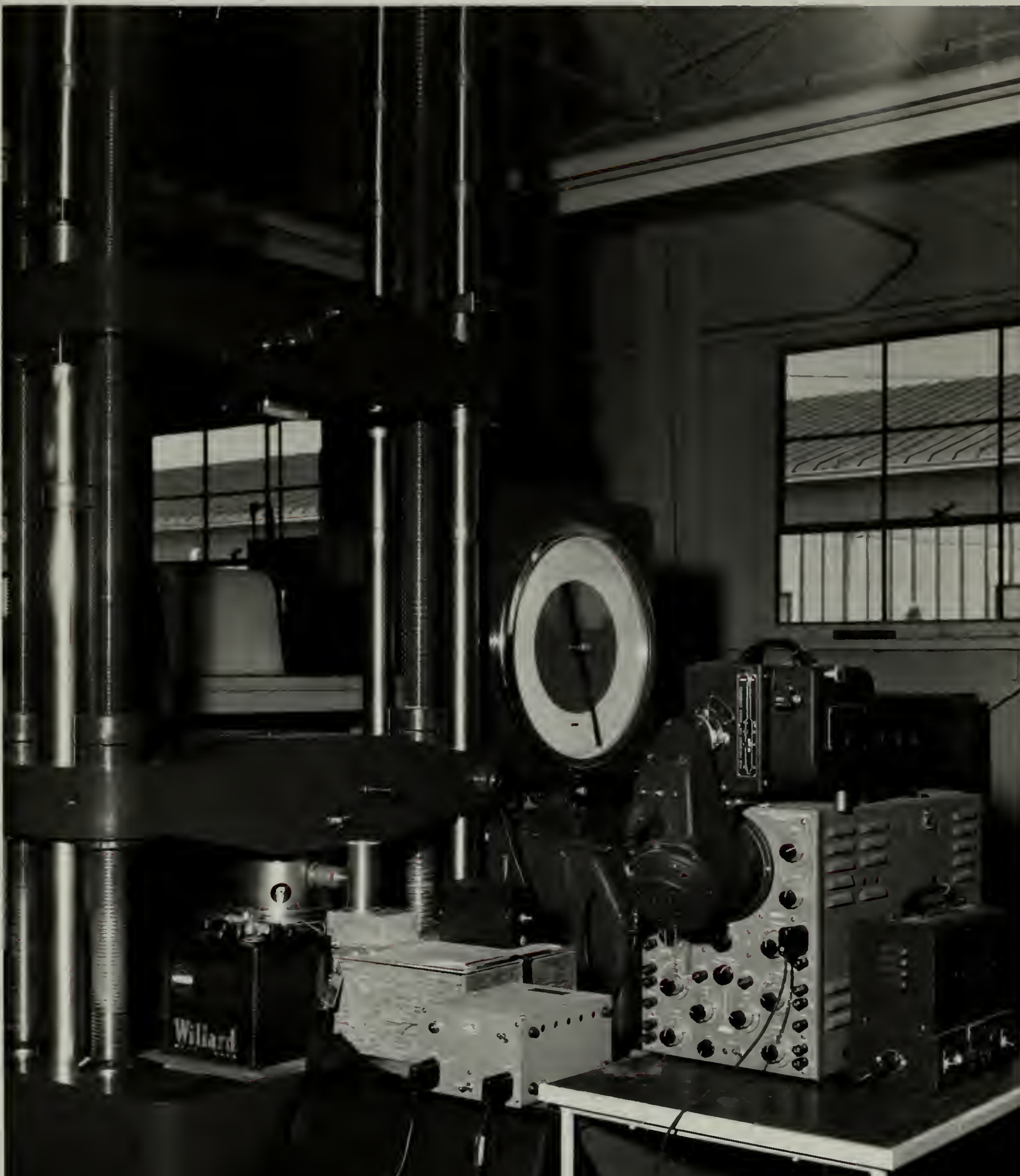

Figure 4

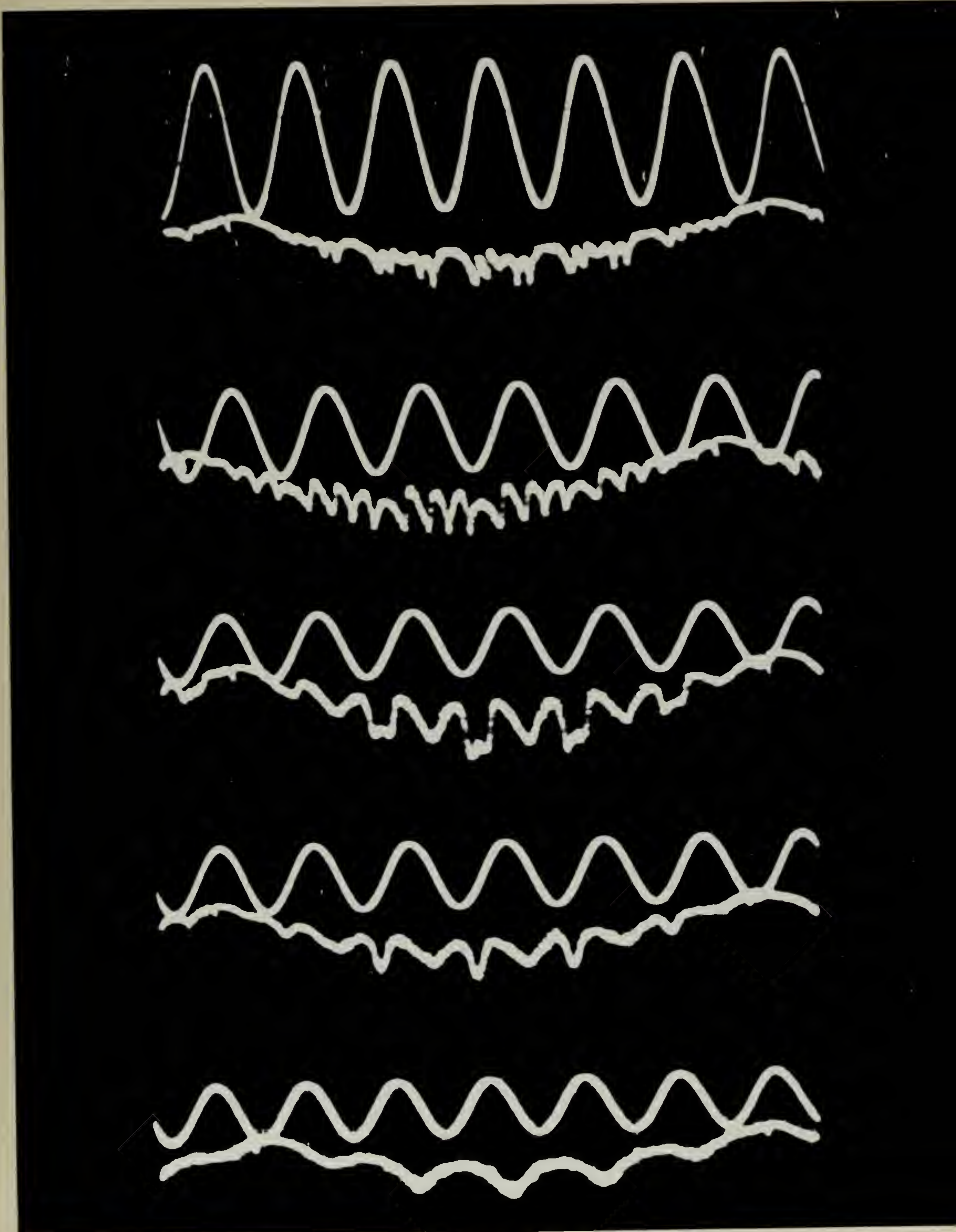

Figure 5

Figure 6

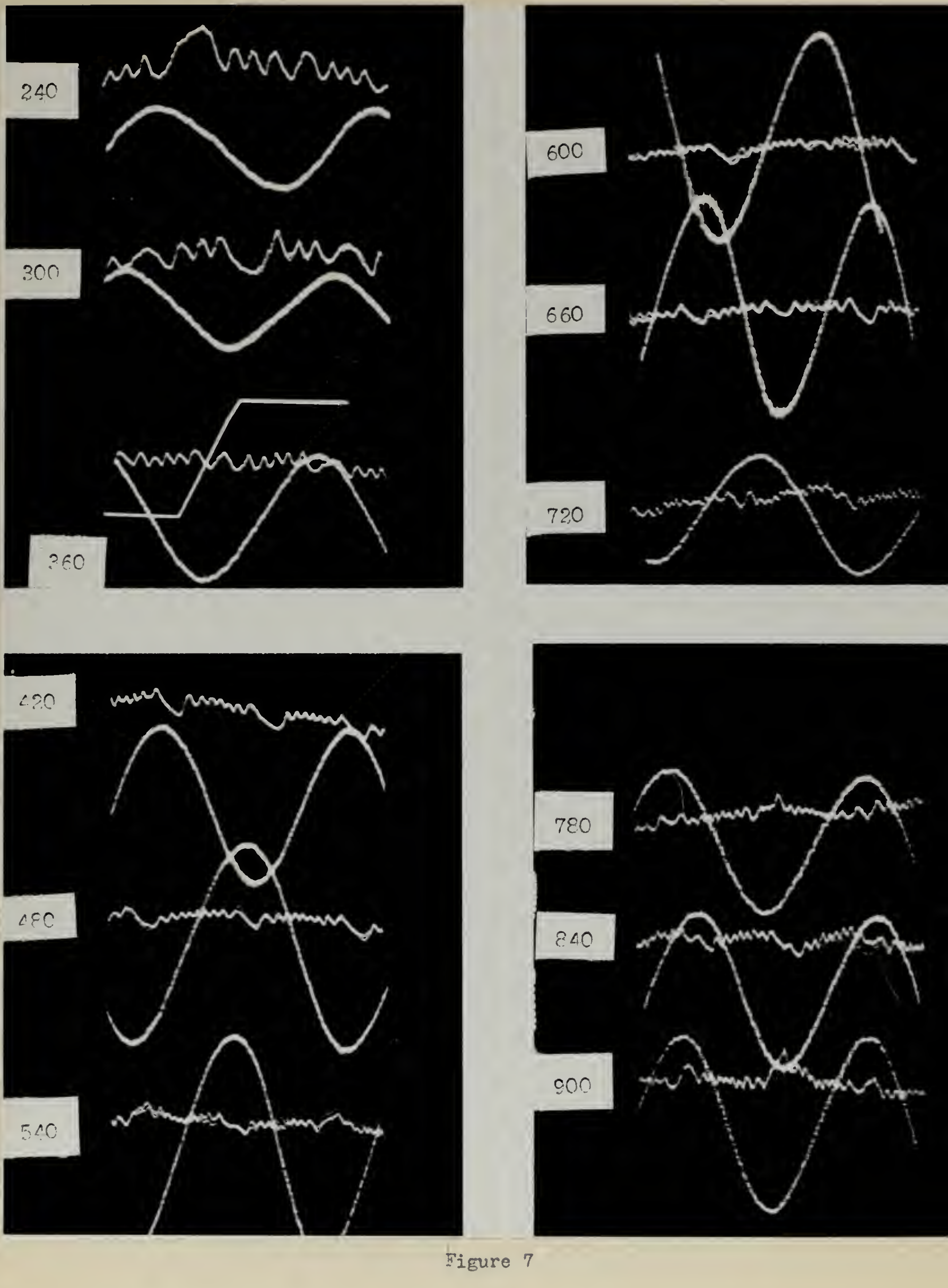

Figure 7

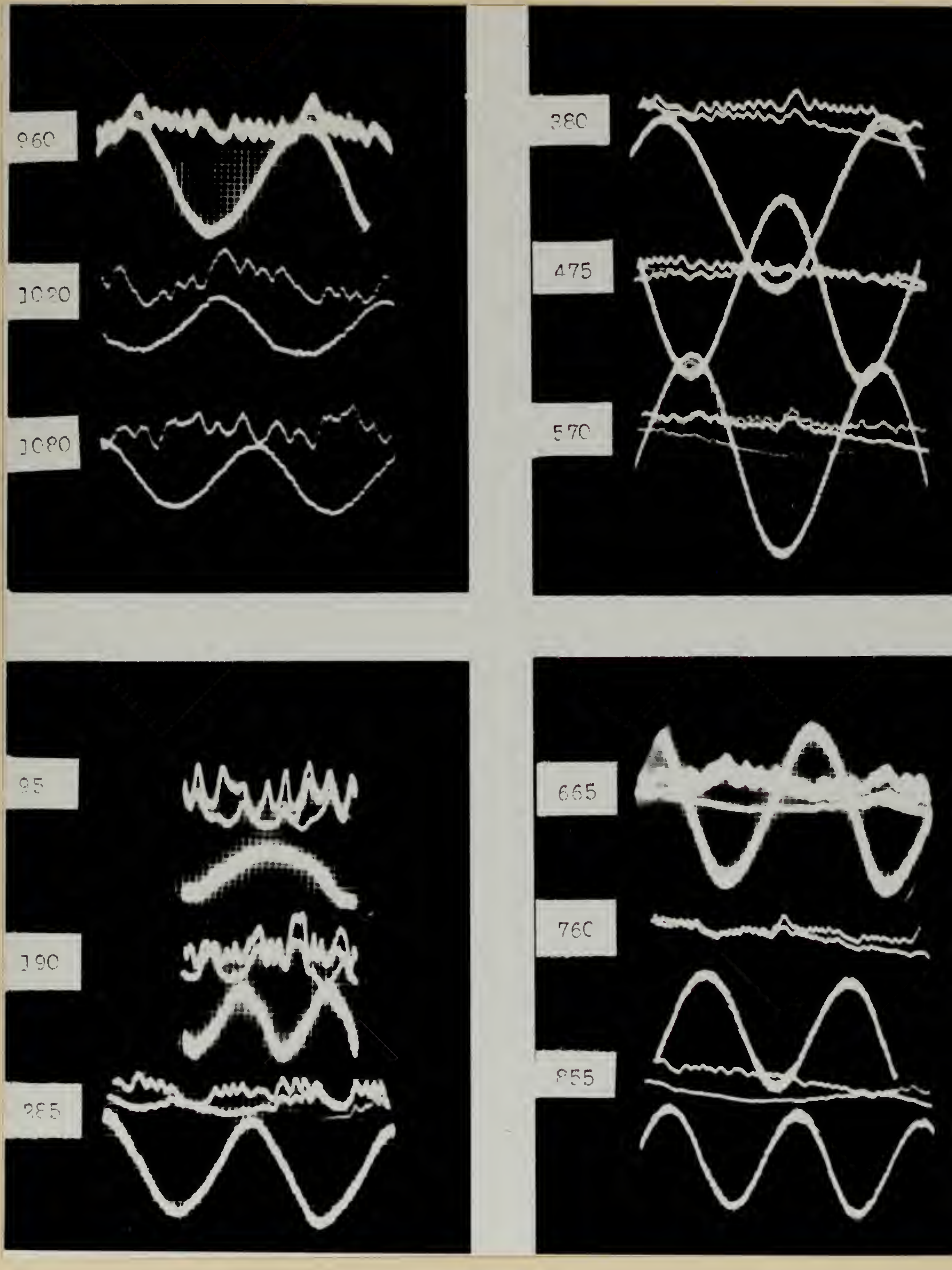

Figure 8